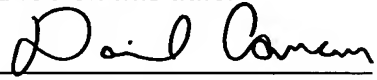


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MAGNETIC RECORDING MEDIUM AND  
MAGNETIC STORAGE APPARATUS

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MAGNETIC RECORDING MEDIUM AND MAGNETIC  
STORAGE APPARATUS

BACKGROUND OF THE INVENTION

This application claims the benefit of a Japanese Patent Application No.2001-272601 filed September 7, 2001, the disclosure of which is hereby incorporated by reference.

1. Field of the Invention

The present invention generally relates to magnetic recording media and magnetic storage apparatuses, and more particularly to a magnetic recording medium which is suited for high-density recording and capable of carrying out high-speed recording and reproduction, and to a magnetic storage apparatus which uses such a magnetic recording medium.

2. Description of the Related Art

Due to the developments in information processing technology, there are increased demands for high-density magnetic recording media. For example, for a hard disk, the magnetic recording media required to satisfy such demands should include such characteristics as low noise and improved thermal stability.

The recording density of longitudinal magnetic recording media, such as magnetic disks, has been increased considerably due to the reduction

1 of medium noise and the development of  
2 magnetoresistive and high-sensitivity spin-valve  
3 heads. A typical magnetic recording medium is  
4 comprised of a substrate, an underlayer, a magnetic  
5 layer, and a protection layer which are successively  
6 stacked in this order. The underlayer is made of Cr  
7 or a Cr alloy, and the magnetic layer is made of a  
8 Co alloy.

9 Various methods have been proposed to  
10 reduce the medium noise. For example, Okamoto et  
11 al., "Rigid Disk Medium For 5 Gbit/in<sup>2</sup> Recording",  
12 AB-3, Intermag '96 Digest, proposes decreasing the  
13 grain size and size distribution of the magnetic  
14 layer by reducing the magnetic layer thickness by  
15 the proper use of an underlayer made of CrMo. U.S.  
16 Patent No. 5,693,426 proposes the use of an  
17 underlayer made of NiAl. Further, Hosoe et al.,  
18 "Experimental Study of Thermal Decay in High-Density  
19 Magnetic Recording Media", IEEE Trans. Magn. Vol.33,  
20 1528 (1997), for example, proposes the use of an  
21 underlayer made of CrTiB. The underlayers described  
22 above also promote c-axis orientation of the  
23 magnetic layer in a plane which increases the  
24 remanence magnetization and the thermal stability of  
25 the written bits. In addition, proposals have been  
26 made to reduce the thickness of the magnetic layer,  
27 to increase the resolution or to decrease the width  
28 of the transition between written bits. Furthermore,  
29 proposals have been made to decrease the exchange  
30 coupling between grains by promoting more Cr  
31 segregation in a magnetic layer which is made of the  
32 CoCr alloy.

33 However, as the grains of the magnetic  
34 layer become smaller and more magnetically isolated  
35 from each other, the written bits become unstable  
36 due to thermal activation and to demagnetizing  
37 fields which increase with linear density. Lu et  
38 al., "Thermal Instability at 10 Gbit/in<sup>2</sup> Magnetic

1 Recording", IEEE Trans. Magn. Vol.30, 4230 (1994)  
2 demonstrated, by micromagnetic simulation, that  
3 exchange-decoupled grains having a diameter of 10 nm  
4 and the ratio  $K_u V / k_B T \sim 60$  in 400 kfc i di-bits are  
5 susceptible to significant thermal decay, where  $K_u$   
6 denotes the magnetic anisotropy constant,  $V$  denotes  
7 the average magnetic grain volume,  $k_B$  denotes the  
8 Boltzmann constant, and  $T$  denotes the temperature.  
9 The ratio  $K_u V / k_B T$  is also referred to as a thermal  
10 stability factor.

11 It has been reported in Abarra et al.,  
12 "Thermal Stability of Narrow Track Bits in a 5  
13 Gbit/in<sup>2</sup> Medium", IEEE Trans. Magn. Vol.33, 2995  
14 (1997), that the presence of intergranular exchange  
15 interaction stabilizes written bits, as demonstrated  
16 by MFM studies of annealed 200 kfc i bits on a 5  
17 Gbit/in<sup>2</sup> CoCrPtTa/CrMo medium. However, more grain  
18 decoupling is essential for recording densities of  
19 20 Gbit/in<sup>2</sup> or greater.

20 The obvious solution has been to increase  
21 the magnetic anisotropy of the magnetic layer. But  
22 unfortunately, the increased magnetic anisotropy  
23 places a great demand on the head write field which  
24 degrades the "overwrite" performance, which is the  
25 ability to write over previously written data.

26 In addition, the coercivity of thermally  
27 unstable magnetic recording medium increases rapidly  
28 with decreasing switching time, as reported in He et  
29 al., "High Speed Switching in Magnetic Recording  
30 Media", J. Magn. Magn. Mater. Vol.155, 6 (1996), for  
31 magnetic tape media, and in J. H. Richter, "Dynamic  
32 Coercivity Effects in Thin Film Media", IEEE Trans.  
33 Magn. Vol.34, 1540 (1997), for magnetic disk media.  
34 Consequently, adverse effects are introduced in the  
35 data rate, that is, how fast data can be written on  
36 the magnetic layer and the amount of head field  
37 required to reverse the magnetic grains.

1                   On the other hand, another proposed method  
2   of improving the thermal stability increases the  
3   orientation ratio of the magnetic layer by  
4   appropriately texturing the substrate under the  
5   magnetic layer. For example, Akimoto et al.,  
6   "Relationship Between Magnetic Circumferential  
7   Orientation and Magnetic Thermal Stability", J. Magn.  
8   Magn. Mater. (1999), in press, report through  
9   micromagnetic simulation that the effective ratio  
10   $K_u V / k_B T$  is enhanced by a slight increase in the  
11  orientation ratio. This further results in a weaker  
12  time dependence for the coercivity which improves  
13  the overwrite performance of the magnetic recording  
14  medium, as reported in Abarra et al., "The Effect of  
15  Orientation Ratio on the Dynamic Coercivity of Media  
16  for >15 Gbit/in<sup>2</sup> Recording", EB-02, Intermag '99,  
17  Korea.

18                   Furthermore, keepered magnetic recording  
19  media have been proposed for thermal stability  
20  improvement. The keeper layer is made up of a  
21  magnetically soft layer that is parallel to the  
22  magnetic layer. This soft layer can be disposed  
23  either above or below the magnetic layer.  
24  Oftentimes, a Cr isolation layer is interposed  
25  between the soft layer and the magnetic layer. The  
26  soft layer reduces the demagnetizing fields in the  
27  written bits on the magnetic layer. However,  
28  coupling the magnetic layer to a continuously-  
29  exchanged coupled soft layer defeats the purpose of  
30  decoupling the grains of the magnetic layer. As a  
31  result, the medium noise increases.

32                   In order to improve the thermal stability  
33  and to reduce the medium noise, magnetic recording  
34  media and magnetic storage apparatuses have been  
35  proposed in U.S. Patent Application S.N.09/425,788  
36  filed October 22, 1999, which is incorporated herein  
37  by reference, and in which the assignee is the same  
38  as the assignee of this application. This

1 previously proposed magnetic recording medium is  
2 comprised of at least one exchange layer structure,  
3 and a magnetic layer formed on the exchange layer  
4 structure, wherein the exchange layer structure  
5 includes a ferromagnetic layer and a non-magnetic  
6 coupling layer provided on the ferromagnetic layer  
7 and under the magnetic layer, and the ferromagnetic  
8 layer and the magnetic layer have antiparallel  
9 magnetizations. According to this previously  
10 proposed magnetic recording medium, it is possible  
11 to improve the thermal stability of the written bits,  
12 reduce the medium noise, and realize a high-density  
13 recording having a high reliability without  
14 adversely affecting the performance of the magnetic  
15 recording medium.

16 In other words, in this previously  
17 proposed magnetic recording medium, the non-magnetic  
18 coupling layer (or the non-magnetic exchange layer)  
19 is interposed between the ferromagnetic layer that  
20 forms a first magnetic layer and the magnetic layer  
21 that forms a second magnetic layer. When the  
22 structure includes first and second magnetic layers  
23 having antiparallel magnetizations, the first and  
24 second magnetic layers mutually cancel portions of  
25 the magnetizations. Hence, it is possible to  
26 increase the effective grain size of the magnetic  
27 layer without substantially affecting the resolution.  
28 Therefore, from the point of view of the grain  
29 volume, it is possible to increase the apparent  
30 thickness of the magnetic layer so as to realize a  
31 magnetic recording medium having a good thermal  
32 stability.

33 Accordingly, this previously proposed  
34 magnetic recording medium employs a basic structure  
35 made up of the ferromagnetic layer (the first  
36 magnetic layer) and the magnetic layer (the second  
37 magnetic layer), so as to improve the thermal  
38 stability and to reduce the medium noise.

1           When an external recording magnetic field  
2   is applied to this previously proposed magnetic  
3   recording medium, the first and second magnetic  
4   layers first assume parallel magnetizations, and  
5   when the recording magnetic field decreases to zero  
6   (residual magnetization state) thereafter, the  
7   magnetization of the first magnetic layer is  
8   switched and becomes antiparallel to the  
9   magnetization of the second magnetic layer.

10           However, as the recording density and the  
11   signal transfer rate increase, it becomes necessary  
12   to also increase the recording and reproducing speed.  
13   For this reason, the need to wait for the switching  
14   of the magnetization to occur in the first magnetic  
15   layer after recording may interfere with the  
16   realization of high-speed recording and reproduction.

17           In other words, the first and second  
18   magnetic layers of this previously proposed magnetic  
19   recording medium assume antiparallel magnetizations  
20   in the residual magnetization state, and when the  
21   external recording magnetic field is applied in this  
22   state, the first and second magnetic layers assume  
23   parallel magnetizations. Then, when the recording  
24   magnetic field thereafter decreases to zero to  
25   assume the residual magnetization state once again,  
26   the magnetization of the first magnetic layer is  
27   switched to become antiparallel to the magnetization  
28   of the second magnetic layer. During this process,  
29   it is necessary to wait for the first magnetic layer  
30   to naturally make the magnetization switch.

31           But when the recording speed is increased  
32   and recording to an adjacent bit is made before the  
33   first magnetic layer makes the magnetization switch,  
34   the position of the bit which is to be recorded may  
35   shift due to a counter magnetic field from the bit  
36   in the parallel magnetization state. In this case,  
37   a non-linear transition shift (NLTS) deteriorates,  
38   and adversely affects the recording.

1           On the other hand, when measures are taken  
2   to reduce the time from recording to reproduction,  
3   an abnormal signal is generated to prevent normal  
4   reproduction if the reproduction is carried out  
5   before the first magnetic layer is switched to the  
6   antiparallel magnetization state from the parallel  
7   magnetization state.

8  
9                   SUMMARY OF THE INVENTION

10           Accordingly, it is a general object of the  
11   present invention to provide a novel and useful  
12   magnetic recording medium and magnetic storage  
13   apparatus, in which the problems described above are  
14   eliminated.

15           Another and more specific object of the  
16   present invention is to provide a magnetic recording  
17   medium which has first and second magnetic layers  
18   with antiparallel magnetizations to realize improved  
19   thermal stability and reduced medium noise, and that  
20   is capable of carrying out magnetic recording and  
21   reproduction at a high speed, and to provide a  
22   magnetic storage apparatus which employs such a  
23   magnetic recording medium.

24           Still another object of the present  
25   invention is to provide a magnetic recording medium  
26   comprising a first magnetic layer, a second magnetic  
27   layer, and a non-magnetic coupling layer provided  
28   between the first and second magnetic layers so that  
29   the first and second magnetic layers are exchange-  
30   coupled and magnetizations of the first and second  
31   magnetic layers are antiparallel, where the first  
32   magnetic layer has an exchange coupling field  $H_{ex1}$   
33   which is larger than respective coercivities  $H_{c1}$  and  
34    $H_{c2}$  of the first and second magnetic layers.  
35   According to the magnetic recording medium of the  
36   present invention, the magnetizations of the first  
37   and second magnetic layers can be maintained  
38   antiparallel in a residual magnetization state, and



1 it is possible to realize a high recording density  
2 and high-speed recording and reproduction.

3 A switching field  $H_{sw}^*$  which switches the  
4 magnetization of the first magnetic layer to become  
5 parallel to the magnetization of the second magnetic  
6 layer may be set to a sum of the exchange coupling  
7 field  $H_{ex1}$  and the coercivity  $H_{c1}$  of the first  
8 magnetic layer. In this case, it is possible to set  
9 a recording field within a range which does not  
10 reach the level of the switching field  $H_{sw}^*$ , so that  
11 it is possible to positively realize a magnetic  
12 recording medium in which the magnetizations of the  
13 first and second magnetic layers are rotated while  
14 maintaining antiparallel magnetizations of the first  
15 and second magnetic layers.

16 A magnetization and thickness product  
17  $t_1 M_{s1}$  of the first magnetic layer is preferably  
18 smaller than a magnetization and thickness product  
19  $t_2 M_{s2}$  of the second magnetic layer, where  $t_1$  denotes  
20 a thickness of the first magnetic layer,  $M_{s1}$  denotes  
21 a magnetization of the first magnetic layer,  $t_2$   
22 denotes a thickness of the second magnetic layer,  
23 and  $M_{s2}$  denotes a magnetization of the second  
24 magnetic layer. In this case, it is possible to  
25 increase the exchange coupling field  $H_{ex1}$  of the  
26 first magnetic layer having a small magnetization  
27 and thickness product  $t_1 M_{s1}$ , so that it is possible  
28 to more positively realize a magnetic recording  
29 medium in which the exchange coupling field  $H_{ex1}$  is  
30 larger than the coercivities  $H_{c1}$  and  $H_{c2}$  of the  
31 first and second magnetic layers.

32 The coercivity  $H_{c1}$  of the first magnetic  
33 recording medium is preferably smaller than the  
34 coercivity  $H_{c2}$  of the second magnetic recording  
35 medium. In this case, it is possible to determine a  
36 main-sub relationship of the first and second  
37 magnetic layers. In other words, it is possible to  
38 design a magnetic recording medium in which the

1 second magnetic layer, which is set to have the  
2 large coercivity  $H_{c2}$ , is used as the main recording  
3 layer.

4 The magnetic recording medium may further  
5 comprise a coupling intensifying region, provided  
6 near the boundary of the non-magnetic coupling layer  
7 and at least one of the first and second magnetic  
8 layers, for intensifying the exchange coupling  
9 strength between the first and second magnetic  
10 layers. Further, the coupling intensifying region  
11 may be made of a material selected from a group  
12 consisting of Fe, Co, Ni and alloys thereof. With  
13 the coupling intensifying region, it is possible to  
14 obtain an exchange coupling field  $H_{ex}$  which further  
15 increases the exchange coupling between the first  
16 and second magnetic layers.

17 A further object of the present invention  
18 is to provide a patterned medium comprising a  
19 recording surface, and a plurality of unit recording  
20 portions, provided on the recording surface, having  
21 boundaries which are separated among adjacent unit  
22 recording portions. Each of the plurality of unit  
23 recording portions preferably has a stacked  
24 structure comprising a first magnetic layer, a  
25 second magnetic layer, and a non-magnetic coupling  
26 layer provided between the first and second magnetic  
27 layers so that the first and second magnetic layers  
28 are exchange-coupled and magnetizations of the  
29 first and second magnetic layers are antiparallel,  
30 where the first magnetic layer has an exchange  
31 coupling field  $H_{ex1}$  which is larger than respective  
32 coercivities  $H_{c1}$  and  $H_{c2}$  of the first and second  
33 magnetic layers. According to the patterned medium  
34 of the present invention, it is possible to realize  
35 a high recording density and high-speed recording  
36 and reproduction.

37 Another object of the present invention is  
38 to provide a magnetic storage apparatus comprising

1 at least one magnetic recording medium, and at least  
2 one head for applying a field to the magnetic  
3 recording medium, where the magnetic recording  
4 medium comprises a first magnetic layer, a second  
5 magnetic layer, and a non-magnetic coupling layer  
6 provided between the first and second magnetic  
7 layers so that the first and second magnetic layers  
8 are exchange-coupled and magnetizations of the first  
9 and second magnetic layers are antiparallel, and the  
10 first magnetic layer has an exchange coupling field  
11  $H_{ex1}$  which is larger than respective coercivities  
12  $H_{c1}$  and  $H_{c2}$  of the first and second magnetic layers.  
13 According to the magnetic storage apparatus of the  
14 present invention, it is possible to realize high  
15 recording density and high-speed recording and  
16 reproduction.

17 The field from the head may be larger than  
18 a coercivity  $H_{c2}$  of the second magnetic layer and  
19 smaller than a switching field  $H_{sw}^*$  which switches  
20 the magnetization of the first magnetic layer to  
21 become parallel to the magnetization of the second  
22 magnetic layer. Moreover, the switching field  $H_{sw}^*$   
23 may be set to the sum of the exchange coupling field  
24  $H_{ex1}$  and the coercivity  $H_{c1}$  of the first magnetic  
25 layer. In these cases, it is possible to positively  
26 realize the high-speed recording.

27 Other objects and further features of the  
28 present invention will be apparent from the  
29 following detailed description when read in  
30 conjunction with the accompanying drawings.

#### 31 BRIEF DESCRIPTION OF THE DRAWINGS

32 FIG. 1 is a cross-sectional view showing  
33 the main parts of one embodiment of a magnetic  
34 recording medium according to the present invention;

35 FIG. 2 is an enlarged cross-sectional view  
36 showing the main parts of a modification of the FIG.  
37 1 embodiment of the magnetic recording medium;

1                   FIG. 3 is a diagram showing a hysteresis  
2   loop of the FIG. 2 modification of the magnetic  
3   recording medium;

4                   FIGS. 4A and 4B respectively are diagrams  
5   showing switching of the magnetizations in the FIG.  
6   2 modification of the magnetic recording medium and  
7   a previously proposed magnetic recording medium;

8                   FIG. 5 is a diagram showing a portion of a  
9   recording surface of a patterned medium on an  
10  enlarged scale;

11                  FIG. 6 is a cross-sectional view showing  
12   the main parts of one embodiment of a magnetic  
13   storage apparatus according to the present  
14   invention; and

15                  FIG. 7 is a plan view showing the main  
16   parts of the magnetic storage apparatus shown in FIG.  
17   6.

#### 18                   DESCRIPTION OF THE PREFERRED EMBODIMENTS

19                  FIG. 1 is a cross-sectional view showing  
20   the main parts of one embodiment of a magnetic  
21   recording medium according to the present invention.  
22   A magnetic recording medium 10 shown in FIG. 1  
23   includes a non-magnetic substrate 11, a seed layer  
24   12, an underlayer 13, a non-magnetic intermediate  
25   layer 14, a first magnetic layer 15, a non-magnetic  
26   coupling layer 16, a second magnetic layer 17, and a  
27   protection layer 18 which are successively stacked  
28   in this order. The magnetic recording medium 10 can  
29   be produced by sputtering, for example. A lubricant  
30   layer 19 may further be provided on top of the  
31   protection layer 18.

32                  The non-magnetic substrate 11 is made of  
33   for example, Al, glass or Si. The non-magnetic  
34   substrate 11 may be mechanically textured, if  
35   desired, but such texturing is not required.

36                  The seed layer 12 may be made of NiP or  
37   NiAl, for example, but the seed layer 12 is

1 preferably made of NiP, for example, especially in  
2 the case where the non-magnetic substrate 11 is made  
3 of Al or an Al alloy. The seed layer 12 may or may  
4 not be oxidized, and may or may not be mechanically  
5 textured. The seed layer 12 may be made of a B2  
6 structure alloy such as NiAl and FeAl when the non-  
7 magnetic substrate 11 is made of glass, for example.  
8 The seed layer 12 is provided to promote a (001) or  
9 (112) texture of the underlayer 13 which is formed  
10 on the seed layer 12. The underlayer 13 may be made  
11 of Cr or a Cr alloy, similarly as in the case of a  
12 conventional magnetic recording medium.

13 In a case where the magnetic recording  
14 medium 10 is a magnetic disk, the mechanical  
15 texturing provided on the non-magnetic substrate 11  
16 or the seed layer 12 which is made of NiP is made in  
17 a circumferential direction of the magnetic disk,  
18 that is, in the direction in which the tracks of the  
19 magnetic disk extend.

20 The non-magnetic intermediate layer 14 is  
21 provided to further promote epitaxy, narrow the  
22 grain distribution of the first magnetic layer 15,  
23 and orient the anisotropy axes (axes of easy  
24 magnetization) of the first magnetic layer 15 along  
25 a plane parallel to the recording surface of the  
26 magnetic recording medium 10. The non-magnetic  
27 intermediate layer 14 is made of an hcp structure  
28 alloy such as CoCr-M, where M = B, Mo, Nb, Ta, W, Cu  
29 or alloys thereof, and has a thickness in a range of  
30 1 to 5 nm.

31 The first magnetic layer 15 is made of a  
32 material such as Co, Ni, Fe, Co alloy, Ni alloy or  
33 the like. In other words, Co alloys such as CoCr,  
34 CoCrTa, CoCrPt and CoCrPt-M, where M = B, Mo, Nb, Ta,  
35 W, Cu or alloys thereof, may be used for the first  
36 magnetic layer 15. Especially when using a Co alloy  
37 for the first magnetic layer 15, the Co  
38 concentration of the Co alloy may be set high, that

1 is, the Co alloy may be Co rich, so as to increase  
2 the exchange coupling magnetic field (hereinafter  
3 simply referred to as an exchange coupling field),  
4 which will be described later. The first magnetic  
5 layer 15 preferably has a thickness in the range of  
6 2 to 30 nm, for example.

7 The non-magnetic coupling layer 16 is made  
8 of a material such as Ru, Rh, Re, Ir, Cr, Cu, Ru  
9 alloy, Rh alloy, Re alloy, Ir alloy, Cr alloy, Cu  
10 alloy or alloys thereof. For example, when the non-  
11 magnetic coupling layer 16 is made of Ru, the non-  
12 magnetic coupling layer 16 has a thickness in the  
13 range of 0.4 to 1.0 nm, and desirably has a  
14 thickness on the order of approximately 0.8 nm. For  
15 this particular thickness range of the non-magnetic  
16 coupling layer 16, the magnetizations of the first  
17 magnetic layer 15 and the second magnetic layer 17  
18 (which will be described later) are antiparallel.

19 The second magnetic layer 17 is made of a  
20 material such as Co or a Co alloy such as CoCr,  
21 CoCrTa, CoCrPt, CoCrPt-M, where M = B, Mo, Nb, Ta, W,  
22 Cu or alloys thereof. Especially when using a Co  
23 alloy for the second magnetic layer 17, the Co  
24 concentration of the Co alloy may be set high, that  
25 is, the Co alloy may be Co rich, so as to make the  
26 exchange coupling field large. For example, the  
27 second magnetic layer 17 preferably has a thickness  
28 in the range of 2 to 30 nm. Of course, the layer  
29 structure of the second magnetic layer 17 is not  
30 limited to a single-layer structure, and the second  
31 magnetic layer 17 may employ a multi-layer structure.

32 The protection layer 18 may be made of C,  
33 for example. In addition, the lubricant layer 19 is  
34 preferably made of an organic lubricant, for example,  
35 for use with a magnetic transducer such as a spin-  
36 valve head. The protection layer 18 and the  
37 lubricant layer 19 form a protection layer structure

1 at the recording surface of the magnetic recording  
2 medium 10.

3 Obviously, the layer structure under the  
4 exchange layer structure is not limited to that  
5 shown in FIG. 1. For example, the underlayer 13 may  
6 be made of Cr or a Cr alloy and formed to a  
7 thickness in the range of 5 to 40 nm on the non-  
8 magnetic substrate 11, and the first magnetic layer  
9 15 may be provided on this underlayer 13. In  
10 addition, although the first and second magnetic  
11 layers 15 and 17 having the antiparallel  
12 magnetizations are respectively formed by one  
13 magnetic layer each in this embodiment, it is  
14 possible, for example, to additionally provide under  
15 the first magnetic layer 15 one or more magnetic  
16 layers having antiparallel magnetization with  
17 respect to an adjacent magnetic layer. In this case,  
18 an exchange coupling field  $H_{ex}$  of each additionally  
19 provided magnetic layer is set larger than a  
20 coercivity  $H_{c2}$  of the second magnetic layer 17, so  
21 that the magnetizations (magnetization directions)  
22 of each additionally provided magnetic layer rotate  
23 together with the first and second magnetic layers  
24 15 and 17.

25 The magnetic recording medium 10 having  
26 the basic structure described above is characterized  
27 in that the first and second magnetic layers 15 and  
28 17 maintain the antiparallel magnetization states at  
29 the time of recording, and the magnetization  
30 directions of the first and second magnetic layers  
31 15 and 17 rotate together. For this reason, it is  
32 desirable that the recording magnetic field  
33 (hereinafter simply referred to as a recording  
34 field) that is applied to the magnetic recording  
35 medium 10 is in a range that does not create a  
36 switching magnetic field (hereinafter simply  
37 referred to as a switching field)  $H_{sw}^*$  that acts to  
38 switch the magnetization of the first magnetic layer

1 15 to become parallel to the magnetization of the  
2 second magnetic layer 17. The position of the  
3 switching field  $H_{sw}^*$  can be found from a coercivity  
4  $H_{c1}$  of the first magnetic layer 15 and an exchange  
5 coupling field  $H_{ex1}$  of the first magnetic layer 15  
6 which is generated by the exchange coupling of the  
7 first and second magnetic layers 15 and 17, as will  
8 be described later in more detail.

9 The exchange coupling field  $H_{ex}$  is the  
10 field which is generated by the exchange coupling of  
11 the first and second magnetic layers 15 and 17.  
12 Generally, the exchange coupling field  $H_{ex1}$  of the  
13 first magnetic layer 15 can be obtained from  $H_{ex1} =$   
14  $J/t_1 M_{s1}$ , where  $J$  denotes an exchange coupling  
15 constant,  $t_1$  denotes a thickness of the first  
16 magnetic layer 15, and  $M_{s1}$  denotes a magnetization  
17 of the first magnetic layer 15. Similarly, an  
18 exchange coupling field  $H_{ex2}$  of the second magnetic  
19 layer 17 can be obtained from  $H_{ex2} = J/t_2 M_{s2}$ , where  
20  $J$  denotes the exchange coupling constant,  $t_2$  denotes  
21 a thickness of the second magnetic layer 17, and  $M_{s2}$   
22 denotes a magnetization of the second magnetic layer  
23 17. In this specification, a description will be  
24 given by focusing on the exchange coupling field  
25  $H_{ex1}$  generated in the first magnetic layer 15.

26 When the exchange coupling field  $H_{ex1}$  is  
27 set to be larger than both the coercivity  $H_{c1}$  of the  
28 first magnetic layer 15 and the coercivity  $H_{c2}$  of  
29 the second magnetic layer 17, it is possible to make  
30 the magnetizations of the first and second magnetic  
31 layers 15 and 17 mutually antiparallel. In addition,  
32 because the desired switching field  $H_{sw}^*$  can be  
33 obtained from the sum of the exchange coupling field  
34  $H_{ex1}$  and the coercivity  $H_{c1}$  of the first magnetic  
35 layer 15, as will be described later, it is possible  
36 to carry out the recording while maintaining the  
37 magnetizations of the first and second magnetic  
38 layers 15 and 17 in an antiparallel state by



1 applying on the magnetic recording medium 10 a  
2 recording field which does not reach the level of  
3 the switching field  $H_{sw}^*$ .

4 Furthermore, when the coercivity  $H_{c1}$  of  
5 the first magnetic layer 15 is set to be large, the  
6 difference between the coercivity  $H_{c2}$  of the second  
7 magnetic layer 17 and the switching field  $H_{sw}^*$  can  
8 be made large, to thereby enable an increased degree  
9 of freedom of design of the magnetic recording  
10 medium 10.

11 In this specification, the switching field  
12  $H_{sw}^*$  refers to the field which switches the  
13 magnetization of the first magnetic layer 15 to  
14 become parallel to the magnetization of the second  
15 magnetic layer 17 when an external field is applied  
16 to the magnetic recording medium 10 while increasing  
17 the field strength, in a state where the coercivity  
18  $H_{c2}$  of the second magnetic layer 17 is smaller than  
19 the exchange coupling field  $H_{ex1}$ .

20 Next, a more detailed description will be  
21 given of the characterizing structures described  
22 above which are included in the magnetic recording  
23 medium 10.

24 In this embodiment, the coercivity  $H_{c2}$  of  
25 the second magnetic layer 17 is set to approximately  
26 4 kOe, and the coercivity  $H_{c1}$  of the first magnetic  
27 layer 15 is set to approximately 0.5 kOe, for  
28 example. Hence, the coercivity  $H_{c2}$  of the second  
29 magnetic layer 17 is sufficiently large compared to  
30 the coercivity  $H_{c1}$  of the first magnetic layer 15.

31 The magnetization and thickness product  
32  $t_2 M_{s2}$  of the second magnetic layer 17 is set to be  
33 larger than the magnetization and thickness product  
34  $t_1 M_{s1}$  of the first magnetic layer 15. For this  
35 reason, the difference that is obtained by  
36 subtracting the magnetization and thickness product  
37  $t_1 M_{s1}$  of the first magnetic layer 15 from the  
38 magnetization and thickness product  $t_2 M_{s2}$  of the

1 second magnetic layer 17 mainly contributes to the  
2 signal at the time of the reproduction. In addition,  
3 since the magnetization and thickness product  $t_1 M_{s1}$   
4 of the first magnetic layer 15 is set to be small,  
5 the exchange coupling field  $H_{ex1}$  can be made large,  
6 because  $H_{ex1} = J/t_1 M_{s1}$  as described above.

7 Furthermore, in the magnetic recording  
8 medium 10 of this embodiment, it is desirable to  
9 provide a coupling intensifying region for  
10 intensifying the exchange coupling strength between  
11 the second magnetic layer 17 and the first magnetic  
12 layer 15, in addition to the basic structure shown  
13 in FIG. 1.

14 FIG. 2 is an enlarged cross-sectional view  
15 showing a portion of a modification of the FIG. 1  
16 embodiment of the magnetic recording medium 10 that  
17 includes the coupling intensifying region. More  
18 particularly, FIG. 2 shows the layer structure of  
19 the part of this modification of the magnetic  
20 recording medium 10, including a coupling  
21 intensifying region provided between the non-  
22 magnetic coupling layer 16 and the first and second  
23 magnetic layers 15 and 17.

24 In the layer structure shown in FIG. 2, a  
25 lower coupling intensifying region 21 is provided  
26 between the first magnetic layer 15 and the non-  
27 magnetic coupling layer 16, and an upper coupling  
28 intensifying region 22 is provided between the non-  
29 magnetic coupling layer 16 and the second magnetic  
30 layer 17. However, it is not essential to provide  
31 both the upper and lower coupling intensifying  
32 regions 21 and 22, and only one of the upper and  
33 lower coupling intensifying regions 21 and 22 may be  
34 provided. The magnetization of the lower coupling  
35 intensifying region 21 is parallel to the  
36 magnetization of the first magnetic layer 15, and  
37 the magnetization of the upper coupling intensifying  
38 region 22 is parallel to the magnetization of the

1 second magnetic layer 17. The lower coupling  
2 intensifying region 21, together with the first  
3 magnetic layer 15, has a function of intensifying  
4 the exchange coupling between the first and second  
5 magnetic layers 15 and 17. Similarly, the upper  
6 coupling intensifying region 22, together with the  
7 second magnetic layer 17, has a function of  
8 intensifying the exchange coupling between the first  
9 and second magnetic layers 15 and 17. The exchange  
10 coupling between the first and second magnetic  
11 layers 15 and 17 can be intensified even when only  
12 one of the upper and lower coupling intensifying  
13 regions 22 and 21 is provided.

14 The lower coupling intensifying region 21  
15 may be formed as a portion of either the first  
16 magnetic layer 15 or the non-magnetic coupling layer  
17 16, or it may be formed as an interface on the  
18 surface of the first magnetic layer 15 or on the  
19 non-magnetic coupling layer 16. In addition, the  
20 lower coupling intensifying region 21 may be formed  
21 as a full layer with a relatively uniform thickness  
22 or it may be formed as a series of projections.  
23 Similarly, the upper coupling intensifying region 22  
24 may be formed as a portion of either the second  
25 magnetic layer 17 or the non-magnetic coupling layer  
26 16, or it may be formed as an interface on the  
27 surface of the second magnetic layer 17 or the non-  
28 magnetic coupling layer 16. Further, the upper  
29 coupling intensifying region 22 may be formed as a  
30 full layer with a relatively uniform thickness or it  
31 may be formed as a series of projections.

32 The upper and lower coupling intensifying  
33 regions 22 and 21 are preferably made of Fe, Co, Ni  
34 or alloys thereof. It is particularly desirable to  
35 use materials such as Co, CoCr and CoCrTa for the  
36 upper and lower coupling intensifying regions 22 and  
37 21. Moreover, the upper and lower coupling  
38 intensifying regions 22 and 21 may also be made of

1 Co-X, CoCr-Y or CoCrTa-Y, where X = Pt, Ta, B, Cu, W,  
2 Mo, Nb, Ru, Rh, Ir or alloys thereof, and Y = Pt, B,  
3 Cu, W, Mo, Nb, Ru, Rh, Ir or alloys thereof.

4 It is desirable that the maximum thickness  
5 of the material forming each of the upper and lower  
6 coupling intensifying regions 22 and 21 is limited  
7 to approximately 2 nm. In addition, the material  
8 forming each of the upper and lower coupling  
9 intensifying regions 22 and 21 may exist in a  
10 surface state or in a dispersed state. For example,  
11 the function of intensifying the exchange coupling  
12 strength is sufficiently displayed even in a state  
13 where a desired material used is dispersed in a  
14 granular state within or on the surface of the first  
15 magnetic layer 15, for example. Accordingly, even  
16 in a state where only a small amount of the desired  
17 material is dispersed within or on the surface of  
18 the first magnetic layer 15, for example, the  
19 dispersed material as a whole can sufficiently  
20 function as a coupling intensifying region.

21 The thickness of the desired material  
22 within each of the upper and lower coupling  
23 intensifying regions 22 and 21 is approximately 2.0  
24 nm or less. Because the characteristics required of  
25 the magnetic recording medium 10 change depending on  
26 the material that is used to form the upper and  
27 lower coupling intensifying regions 22 and 21, it is  
28 desirable to determine the thickness of the material  
29 forming each of the upper and lower coupling  
30 intensifying regions 22 and 21 by taking such  
31 factors into consideration.

32 The materials such as Fe, Co, Ni and  
33 alloys thereof, which are suited for forming the  
34 upper and lower coupling intensifying regions 22 and  
35 21, may also be used to form the first and second  
36 magnetic layers 15 and 17. Hence, the composition  
37 of the material forming the upper and lower coupling  
38 intensifying regions 22 and 21 may be the same as,

1 or similar to, the composition of the material  
2 forming the upper and lower magnetic layers 15 and  
3 17. However, it is desirable that the material  
4 forming the upper and lower coupling intensifying  
5 regions 22 and 21 is richer in Co (or the like)  
6 compared to the material forming the first and  
7 second magnetic layers 15 and 17. For example,  
8 compared to materials which include Co and are  
9 generally used to form a magnetic layer, it is  
10 desirable that the Co-content of the material  
11 forming the upper and lower coupling intensifying  
12 regions 22 and 21 is at least 10 at% to 20 at%  
13 richer. Therefore, even in a case where materials  
14 having similar compositions are used for the upper  
15 and lower coupling intensifying regions 22 and 21  
16 and the first and second magnetic layers 15 and 17,  
17 the upper and lower coupling intensifying regions 22  
18 and 21 are Co rich compared to the first and second  
19 magnetic layers 15 and 17.

20 The materials described above which are  
21 rich in Co (or the like) may also be used to form  
22 the first and second magnetic layers 15 and 17. In  
23 this case, the lower coupling intensifying region 21  
24 is included in the first magnetic layer 15, and the  
25 surface of the first magnetic layer 15 (that is, the  
26 interface between the first magnetic layer 15 and  
27 the non-magnetic coupling layer 16) substantially  
28 corresponds to the lower coupling intensifying  
29 region 21. In addition, the upper coupling  
30 intensifying region 22 is included in the second  
31 magnetic layer 17, and the surface of the second  
32 magnetic layer 17 (that is, the interface between  
33 the second magnetic layer 17 and the non-magnetic  
34 coupling layer 16) substantially corresponds to the  
35 upper coupling intensifying region 22. Hence, it is  
36 unnecessary in this case to prepare a material for  
37 separately forming the upper and lower coupling  
38 intensifying regions 22 and 21.

1                   Accordingly,       the       lower       coupling  
2   intensifying region 21 simply needs to exist  
3   substantially at a boundary of the first magnetic  
4   layer 15 and the non-magnetic coupling layer 16, and  
5   the upper coupling intensifying region 22 simply  
6   needs to exist substantially at a boundary of the  
7   second magnetic layer 17 and the non-magnetic  
8   coupling layer 16.

9                   In this modification, the upper and lower  
10   coupling intensifying regions 22 and 21 are  
11   preferably respectively made of Co having a  
12   thickness of 1 nm. By employing the layer structure  
13   which includes the upper and lower coupling  
14   intensifying regions 22 and 21, the exchange  
15   coupling strength between the first and second  
16   magnetic layers 15 and 17 is increased. In addition,  
17   among the coercivity  $H_{c2}$  of the second magnetic  
18   layer 17, the coercivity  $H_{c1}$  of the first magnetic  
19   layer 15 and the exchange coupling field  $H_{ex1}$  of the  
20   first magnetic layer 15, both the coercivities  $H_{c1}$   
21   and  $H_{c2}$  are smaller than the exchange coupling field  
22    $H_{ex1}$ . According to this layer structure, the  
23   coercivity  $H_{c12}$  is naturally smaller than the  
24   switching field  $H_{sw}^*$ .

25                  FIG. 3 is a diagram showing a hysteresis  
26   loop of the FIG. 2 modification of the magnetic  
27   recording medium 10. More particularly, FIG. 3  
28   shows the hysteresis loop in which the abscissa  
29   indicates the field and the ordinate indicates the  
30   Kerr signal due to the Kerr effect. It should be  
31   noted that the hysteresis loop of the FIG. 1  
32   embodiment will be of a similar shape to that shown  
33   in FIG. 3, except that the various parameters will  
34   be somewhat shifted.

35                  Arrows ST1 through ST4 indicated in the  
36   upper part of FIG. 3 respectively indicate  
37   magnetization states (i.e., the states of the  
38   direction of magnetization) of the first and second

1 magnetic layers 15 and 17. The hysteresis loop  
2 shown in FIG. 3 includes a main hysteresis loop MAR  
3 at a central portion, and a sub-hysteresis loop SUR  
4 on both the right and left portions.

5 The large main hysteresis loop MAR is  
6 shown for a case where the magnetizations of the  
7 first and second magnetic layers 15 and 17 rotate  
8 together while maintaining the antiparallel state,  
9 that is, for a case where the state ST2 and the  
10 state ST3 are repeated.

11 On the other hand, the small sub-  
12 hysteresis loop SUR on the right shows a case where  
13 the magnetization of the first magnetic layer 15  
14 switches from the antiparallel state to the parallel  
15 state with respect to the magnetization of the  
16 second magnetic layer 17, and vice versa. In FIG. 3,  
17  $\gamma$  indicates a position of the switching field  $H_{sw}^*$   
18 where the magnetization of the first magnetic layer  
19 switches from the antiparallel state to the parallel  
20 state with respect to the magnetization of the  
21 second magnetic layer 17.

22 The sub-hysteresis loop SUR may be  
23 regarded as a hysteresis loop (minor loop)  
24 indicating the magnetization state of the first  
25 magnetic layer 15. In other words, when a field is  
26 applied in a positive direction (+10 kOe) from a  
27 state (residual magnetization state) indicated by  $\delta$ ,  
28 the sub-hysteresis loop SUR passes the position  $\gamma$   
29 and follows SUR-1 on the right side. In this state,  
30 the magnetization of the first magnetic layer 15  
31 switches from the state ST3, which is antiparallel  
32 to the magnetization of the second magnetic layer 17,  
33 to the state ST4, which is parallel to the  
34 magnetization of the second magnetic layer 17. On  
35 the other hand, when the field is reduced from the  
36 state ST4 (i.e., is reduced by 10 kOe), the sub-  
37 hysteresis loop SUR follows SUR-2 on the left side.  
38 In this state, the magnetization of the first

1 magnetic layer 15 switches from the state ST4 which  
2 is parallel to the magnetization of the second  
3 magnetic layer 17 to the state ST3 which is  
4 antiparallel to the magnetization of the second  
5 magnetic layer 17.

6 Therefore, as may be seen from FIG. 3, the  
7 magnetizations of the first and second magnetic  
8 layers 15 and 17 can be maintained in the  
9 antiparallel state when the recording field is  
10 applied in a range of the main hysteresis loop MAR  
11 in which the applied field is smaller than the  
12 switching field  $H_{sw}^*$ , as indicated by  $\gamma$ .

13 The approximate center of the sub-  
14 hysteresis loop SUR indicates the exchange coupling  
15 field  $H_{ex1}$  of the first magnetic layer 15. In  
16 addition, in the main hysteresis loop MAR,  $\beta$   
17 indicates the strength of the field which rotates  
18 the magnetizations while maintaining the  
19 magnetizations of the first and second magnetic  
20 layers 15 and 17 antiparallel. The strength  $\beta$   
21 approximately corresponds to the coercivity  $H_{c2}$  of  
22 the second magnetic layer 17.

23 The conditions for rotating the  
24 magnetizations of the first and second magnetic  
25 layers 15 and 17 together while maintaining the  
26 magnetizations of the first and second magnetic  
27 layers 15 and 17 antiparallel are that at least the  
28 coercivity  $H_{c2}$  of the second magnetic layer 17 is  
29 smaller than the exchange coupling field  $H_{ex1}$  of the  
30 first magnetic layer 15, and that the field applied  
31 to the magnetic recording medium 10 is not larger  
32 than the switching field  $H_{sw}^*$ .

33 Since the sub-hysteresis loop SUR may be  
34 regarded as indicating the magnetization state of  
35 the first magnetic layer 15 as described above, a  
36 difference between the exchange coupling field  $H_{ex1}$   
37 of the first magnetic layer 15 and the switching  
38 field  $H_{sw}^*$  may be regarded as the coercivity  $H_{c1}$  of



1 the first magnetic layer 15. Hence, the switching  
2 field  $H_{sw}^*$  is equal to the sum of the exchange  
3 coupling field  $H_{ex1}$  and the coercivity  $H_{c1}$  of the  
4 first magnetic layer 15 ( $H_{sw}^* = H_{ex1} + H_{c1}$ ).

5 In the particular case shown in FIG. 3,  
6 the coercivity  $H_{c2}$  of the second magnetic layer 17  
7 satisfies the condition  $H_{c2} < H_{ex1}$ , and naturally,  
8  $H_{c2} < (H_{ex1} + H_{c1})$ , and  $H_{c2} < H_{sw}^*$ . In this case,  
9 the position of the switching field  $H_{sw}^*$  can be  
10 prescribed by use of the exchange coupling field  
11  $H_{ex1}$  and the coercivity  $H_{c1}$  of the first magnetic  
12 layer 15, and used when designing the magnetic  
13 recording medium 10.

14 By using a recording field within the  
15 range  $MT$  shown in FIG. 3, which satisfies the  
16 relationship  $H_{c2} < H_{sw}^*$ , it is possible to carry out  
17 the recording on the magnetic recording medium 10  
18 while maintaining the magnetizations of the first  
19 and second magnetic layers 15 and 17 in the  
20 antiparallel state.

21 Although the description above is given  
22 with respect to the sub-hysteresis loop  $SUR$  on the  
23 right in FIG. 3, the sub-hysteresis loop on the left  
24 is approximately symmetrical, with respect to the  
25 origin, to the loop on the right. Accordingly, a  
26 description of the sub-hysteresis loop on the left  
27 will be omitted in this specification.

28 Next, a more detailed description will be  
29 given of the hysteresis loop shown in FIG. 3 with  
30 reference to numerical values. In this modification  
31 of the magnetic recording medium 10, the coupling  
32 intensifying regions 21 and 22 are provided to  
33 intensify the exchange coupling of the first and  
34 second magnetic layers 15 and 17. Accordingly, the  
35 exchange coupling field  $H_{ex}$  between the first and  
36 second magnetic layers 15 and 17 is improved to  
37 approximately 5 kOe, and the switching field  $H_{sw}^*$  is  
38 approximately 5.5 kOe.

1           The exchange coupling field  $H_{ex1}$  of the  
2 first magnetic layer 15 is set to be larger than the  
3 coercivity  $H_{c2}$  of the second magnetic layer 17, and  
4 the coercivity  $H_{c2}$  of the second magnetic layer 17  
5 and the switching field  $H_{sw}^*$  satisfy the  
6 relationship  $H_{c2} < H_{sw}^*$ .

7           When the above described relationships are  
8 satisfied, it is possible to always maintain the  
9 magnetizations of the first and second magnetic  
10 layers 15 and 17 in the antiparallel state while a  
11 recording field is applied from a residual  
12 magnetization state indicated by  $\alpha$  and the  
13 switching of the magnetizations occurs as indicated  
14 by  $\beta$  in FIG. 3. In other words, in the state  $\alpha$   
15 (the residual magnetization state), the  
16 magnetizations of the first and second magnetic  
17 layers 15 and 17 are in the antiparallel state ST2,  
18 but when a recording field is applied in a direction  
19 opposite to the magnetization of the second magnetic  
20 layer 17, the magnetization of the second magnetic  
21 layer 17 switches to the state ST3, approximately at  
22 the position indicated by  $\beta$ , when the recording  
23 field becomes larger than the coercivity  $H_{c2}$  of the  
24 second magnetic layer 17.

25           In this case, the coercivity  $H_{c2}$  of the  
26 second magnetic layer 17 and the exchange coupling  
27 field  $H_{ex1}$  of the first magnetic layer 15 satisfy  
28 the relationship  $H_{c2} < H_{ex1}$ . For this reason, the  
29 first magnetic layer 15 is strongly coupled to the  
30 second magnetic layer 17, and the magnetization of  
31 the first magnetic layer 15 switches simultaneously  
32 with the magnetization of the second magnetic layer  
33 17, while the magnetizations of the first and second  
34 magnetic layers 15 and 17 are maintained  
35 antiparallel. This antiparallel state of the  
36 magnetizations of the first and second magnetic  
37 layers 15 and 17 is maintained in the residual  
38 magnetization state, that is, at the position

1 indicated by  $\delta$  , where the recording field becomes  
2 zero.

3 In other words, in the above described  
4 state where the magnetizations of the first and  
5 second magnetic layers 15 and 17 are maintained  
6 antiparallel, the exchange coupling strength (or  
7 force) which acts to maintain the magnetizations of  
8 the first and second magnetic layers 15 and 17  
9 antiparallel is larger than the external recording  
10 field which is applied to the magnetic recording  
11 medium 10.

12 FIGS. 4A and 4B, respectively, are  
13 diagrams showing switching of the magnetizations in  
14 the present invention of the magnetic recording  
15 medium 10 and a previously proposed magnetic  
16 recording medium which has been proposed in U.S.  
17 Patent Application S.N.09/425,788 described above.

18 In the case of the present magnetic  
19 recording medium 10, the switching process is  
20 completed by switching of the magnetizations once by  
21 a predetermined recording field from state I to  
22 state III or vice versa, as shown in FIG. 4A.

23 But in the case of the previously proposed  
24 magnetic recording medium, the switching of the  
25 state I to the state III can only be realized via a  
26 state II in which the magnetization of the  
27 ferromagnetic layer corresponding to the first  
28 magnetic layer 15 is parallel to the magnetization  
29 of the magnetic layer corresponding to the second  
30 magnetic layer 17. In other words, a transition  
31 from state I to state II and another transition from  
32 state II to state III are required in order to  
33 realize the switching from state I to state III, and  
34 a transition from state III to state II and another  
35 transition from state II to state I are required in  
36 order to realize the switching from state III to  
37 state I.

1                   Therefore, as may be seen from a  
2 comparison of FIGS. 4A and 4B, the present magnetic  
3 recording medium 10 can realize a higher speed of  
4 recording as compared with the previously proposed  
5 magnetic recording medium because of the high-speed  
6 switching of the magnetizations directly from state  
7 I to state III, and vice versa.

8                   In the present invention, the coupling  
9 intensifying region is used to further improve the  
10 exchange coupling between the first and second  
11 magnetic layers 15 and 17. However, the exchange  
12 coupling strength between the first and second  
13 magnetic layers 15 and 17 may also be adjusted by  
14 altering the state of the interface of the material  
15 forming the non-magnetic coupling layer 16. For  
16 example, the exchange coupling strength between the  
17 first and second magnetic layers 15 and 17 may be  
18 adjusted by altering the interface state of Ru which  
19 forms the non-magnetic coupling layer 16. In  
20 addition, the exchange coupling strength between the  
21 first and second magnetic layers 15 and 17 may also  
22 be adjusted and increased by altering the  
23 composition and the thickness of each of the first  
24 and second magnetic layers 15 and 17, by altering  
25 the state of the magnetic grains of each of the  
26 first and second magnetic layers 15 and 17, or by  
27 improving the smoothness of the Ru interface or the  
28 like between the non-magnetic coupling layer 16 and  
29 the first magnetic layer 15 and/or the second  
30 magnetic layer 17. More particularly, the exchange  
31 coupling strength between the first and second  
32 magnetic layers 15 and 17 may be increased by  
33 decreasing the thickness of the first magnetic layer  
34 15 and/or the second magnetic layer 17, by  
35 increasing the Co-content (or the Co concentration)  
36 of the first magnetic layer 15 and/or the second  
37 magnetic layer 17, or by increasing the magnetic

1 grain size of the first magnetic layer 15 and/or the  
2 second magnetic layer 17.

3 On the other hand, the above described  
4 relationship between the coercivity  $H_{c2}$  of the  
5 second magnetic layer 17 and the exchange coupling  
6 field  $H_{ex1}$  of the first magnetic layer 15 may be  
7 maintained, without changing the exchange coupling  
8 strength (that is, maintaining the exchange coupling  
9 strength approximately constant), by decreasing the  
10 coercivity  $H_{c2}$  of the second magnetic layer 17.  
11 More particularly, the coercivity  $H_{c2}$  of the second  
12 magnetic layer 17 may be adjusted by changing the  
13 material, the additives and the production process  
14 of the second magnetic layer 17, so as to change the  
15 microstructure, the crystal structure and the  
16 magnetic domain structure. For example, when  
17 forming the second magnetic layer 17 from CoCrPtB,  
18 it is possible to decrease the coercivity  $H_{c2}$  by  
19 suppressing the Pt-content of CoCrPtB.

20 Furthermore, increasing the coercivity  $H_{c1}$   
21 of the first magnetic layer 15 is also one method of  
22 satisfying the relationship  $H_{c2} < H_{ex1} + H_{c1}$ .  
23 However, if the coercivity  $H_{c1}$  is increased  
24 excessively, there are cases where it is no longer  
25 possible to maintain the antiparallel state of the  
26 magnetizations of the first and second magnetic  
27 layers 15 and 17 in the residual magnetization state.  
28 Accordingly, it is also necessary to design the  
29 coercivity  $H_{c1}$  to be smaller than the exchange  
30 coupling field  $H_{ex1}$ .

31 One important aspect of the magnetic  
32 recording medium 10 of both the FIG. 1 embodiment  
33 and the FIG. 2 modification is that the  
34 magnetizations of the first and second magnetic  
35 layers 15 and 17 are switched, while still  
36 maintaining the magnetizations of the first and  
37 second magnetic layers 15 and 17 antiparallel, by  
38 applying a recording field to the medium 10 that is

1 larger than the coercivity  $H_{c2}$ , and by using various  
2 methods to control the exchange coupling field  $H_{ex1}$   
3 of the first magnetic layer 15, the coercivity  $H_{c2}$   
4 of the second magnetic layer and the coercivity  $H_{c1}$   
5 of the first magnetic layer 15. In addition, the  
6 recording field that is applied to the magnetic  
7 recording medium 10 also needs to be smaller than  
8 the switching field  $H_{sw}^*$ . As a result, it is  
9 possible to carry out a high-speed switching process  
10 that switches the magnetizations of the first and  
11 second magnetic layers 15 and 17 while maintaining  
12 the magnetizations of the first and second magnetic  
13 layers 15 and 17 antiparallel.

14 As may be seen from FIG. 3, if the  
15 recording field applied to the magnetic recording  
16 medium 10 is large when compared to the switching  
17 field  $H_{sw}^*$ , the magnetization of the first magnetic  
18 layer 15 becomes parallel to the magnetization of  
19 the second magnetic layer 17, which is not desirable.  
20 Accordingly, the maximum value of the recording  
21 field should be larger than the coercivity  $H_{c2}$  of  
22 the second magnetic layer 17, but smaller than the  
23 switching field  $H_{sw}^*$ , that is, the maximum recording  
24 field should be set to be within a range between  $\beta$   
25 and  $\gamma$  in FIG. 3. In other words, it is desirable  
26 that the maximum value of the recording field from  
27 the recording head does not exceed the switching  
28 field  $H_{sw}^*$ .

29 Therefore, by controlling the coercivity  
30  $H_{c2}$  of the second magnetic layer 17 and the exchange  
31 coupling field  $H_{ex1}$  of the first magnetic layer 15  
32 so as to satisfy the relationship  $H_{c2} < H_{ex1}$  and by  
33 keeping the recording field from the recording head  
34 from exceeding the switching field  $H_{sw}^*$ , it is  
35 possible to switch the magnetizations of the first  
36 and second magnetic layers 15 and 17 while  
37 maintaining these magnetizations antiparallel.  
38 Unlike the previously proposed magnetic recording

1 medium described above, in the present invention,  
2 state II, in which the magnetizations of the first  
3 and second magnetic layers 15 and 17 become parallel,  
4 does not exist during the recording process, and for  
5 this reason, the present invention can realize  
6 high-speed recording. The deterioration of the non-  
7 linear transition shift (NLTS) due to the causes  
8 described above will thus not occur in the present  
9 invention. In addition, normal reproduction is  
10 possible even when high-speed reproduction is  
11 carried out immediately after recording.

12 FIG. 5 is a diagram showing a portion of a  
13 recording surface of a so-called patterned medium on  
14 an enlarged scale. The patterned medium 30 shown in  
15 FIG. 5 has a storage capacity per unit area several  
16 times greater than those of a conventional magnetic  
17 recording media. Unlike the structures of the  
18 conventional magnetic recording media, the patterned  
19 medium 30 has unit recording portions 31 which are  
20 artificially designed as micro-magnetic recording  
21 regions that are formed by a lithography technique,  
22 or the like. Boundaries of adjacent unit recording  
23 portions 31 are separated on the recording surface  
24 of the patterned medium 30 to thereby realize low  
25 noise. Hence, it is unnecessary to use an additive  
26 such as Cr to promote segregation and grain size  
27 reduction. For this reason, the magnetic layer may  
28 be made of a material having a small additive  
29 content and a large Co-content (Co concentration).  
30 That is, it is possible to use a material that can  
31 obtain a large exchange coupling. As a result, it  
32 is possible to easily satisfy the following  
33 relationship of the exchange coupling field  $H_{ex1}$  of  
34 the first magnetic layer 15, in which the exchange  
35 coupling field  $H_{ex1}$  is larger than the coercivities  
36  $H_{c1}$  and  $H_{c2}$  of the first and second magnetic layers  
37 15 and 17.

1           In another embodiment of the magnetic  
2 recording medium according to the present invention,  
3 the present invention is applied to the patterned  
4 medium 30 described above. More particularly, in  
5 this embodiment, each unit recording portion 31 has  
6 a stacked structure which includes at least the  
7 first magnetic layer 15, the non-magnetic coupling  
8 layer 16 and the second magnetic layer 17 which  
9 satisfy the relationships of the FIG. 1 embodiment  
10 and the FIG. 2 modification described above.  
11 According to this embodiment, it is possible to  
12 realize a magnetic recording medium which has a high  
13 recording density which is further improved and can  
14 carry out high-speed recording and reproduction  
15 which is also further improved.

16           In the embodiments and the modification  
17 described above, the first magnetic layer 15, the  
18 non-magnetic coupling layer 16 and the second  
19 magnetic layer 17 are stacked in this order above  
20 the non-magnetic substrate 11. However, it is of  
21 course possible to stack the second magnetic layer  
22 17, the non-magnetic coupling layer 16 and the first  
23 magnetic layer 15 in this order above the non-  
24 magnetic substrate 11. However, in general, it is  
25 desirable to arrange the magnetic layer which  
26 dominates the recording on the side of the magnetic  
27 recording medium that is closer to the head.

28           Next, a description will be given of an  
29 embodiment of a magnetic storage apparatus according  
30 to the present invention by referring to FIGS. 6 and  
31 7. FIG. 6 is a cross-sectional view showing the  
32 basic parts of this embodiment of the magnetic  
33 storage apparatus according to the present invention,  
34 and FIG. 7 is a plan view of the magnetic storage  
35 apparatus shown in FIG. 6.

36           As shown in FIGS. 6 and 7, the magnetic  
37 storage apparatus 40 generally includes a housing 43.  
38 A motor 44, a hub 45, a plurality of magnetic



1 recording media 46, a plurality of recording and  
2 reproducing heads 47, a plurality of suspensions 48,  
3 a plurality of arms 49, and an actuator unit 41 are  
4 all provided within the housing 43. The magnetic  
5 recording media 46 are mounted on the hub 45 which  
6 is rotated by the motor 44. Each recording and  
7 reproducing head 47 is mounted on the tip end of a  
8 corresponding arm 49 via the suspension 48. The  
9 arms 49 are moved by the actuator unit 41. The  
10 basic construction of this magnetic storage  
11 apparatus is known, and a detailed description  
12 thereof will be omitted in this specification.

13 This embodiment of the magnetic storage  
14 apparatus is characterized by the magnetic recording  
15 media 46. Each magnetic recording medium 46 has the  
16 structure of any of the embodiments and the  
17 modification of the magnetic recording medium  
18 described above in conjunction with FIGS. 1 through  
19 5. In addition, the recording field that is applied  
20 to the magnetic recording medium 46 from the  
21 recording head of the recording and reproducing head  
22 47 is controlled to be both larger than the  
23 coercivity  $H_{c2}$  of the second magnetic layer of the  
24 magnetic recording medium 46 and smaller than the  
25 switching field  $H_{sw}^*$ . Of course, the number of  
26 magnetic recording media 46 is not limited to three,  
27 and for example, one, two, four or more magnetic  
28 recording media 46 may be provided.

29 The basic construction of the magnetic  
30 storage apparatus is not limited to that shown in  
31 FIGS. 6 and 7. In addition, the magnetic recording  
32 medium used in the present invention is not limited  
33 to a magnetic disk.

34 Further, the present invention is not  
35 limited to these embodiments, but various variations  
36 and modifications may be made without departing from  
37 the scope of the present invention.